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Carderock Division
Naval Surface Warfare Center
Bethesda, MD 20084-5000

CARDIVNSWC-TR-81—93/26 August 1993
Machinery Research and Development Directorate
Technical Report

# Liquid Metal-Wetted Niobium Fiber Brushes and Braid Close Clearance Collectors in Magnetic Fields Comparison

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## ABSTRACT

*Niobium fiber brushes wetted with liquid metals offer an alternative to the highly successful braid collector because of the inherent flexibility of the metal fibers. A slipring of niobium fiber brushes wetted with $NaK_{78}$ was compared directly with an NaK braid collector in a model of a 300-kW homopolar generator. Collector tip velocities varied from zero to 67 m/sec, currents from zero to 4,000 A, and magnetic fields from zero to 1.2 T. Results indicate under all conditions the fiber brush collector was comparable or superior to the braid collector.*

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## FIGURES



## ADMINISTRATIVE INFORMATION


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## ABBREVIATIONS

| | |
|---|---|
| MA/m2 | mega amps per meter squared |
| m/sec | meters per second |
| SEM | scanning electron microscope |
| T | tesla |

## BACKGROUND

The development of low-loss, stable current collectors is highly desirable because it makes the implementation of homopolar machinery attractive for a variety of applications.[1] Liquid metals can provide such a collector because their high conductivity and low viscosity result in low losses. On the other hand, implementation of liquid metal collectors in electric machinery has been troublesome because, in addition to the same forces which drive the armature in an electric machine, the liquid metal is also subjected to additional forces resulting from a combination of its nonrigidity and motion in the magnetic field. In general, these forces contribute to a collector which is unstable over the entire operating range of velocity, current, and magnetic field required in typical power applications.

Progress has been made in achieving successfully operating collectors on a laboratory scale (300 kW) by minimizing the gap between the rotor and stator with porous grounding braid.[2,3] Utilization of this technique in large-diameter machinery may not be successful because of the large runouts and shock and vibration loads expected. However, metallic fiber brushes wetted with liquid metals may provide a practical way of maintaining a minimum clearance for large diameter rotors and yet provide a higher degree of insensitivity to runout, shock, and vibration.

Past work in this laboratory has concentrated on fundamental properties of model liquid metal wetted metallic fiber brushes.[4] These brushes were made of niobium and copper and were fabricated by superconducting wire drawing techniques. The brushes were then contoured to the rotor shape, and the copper was acid-etched away to leave the exposed niobium fibers. These experiments were limited to low velocities (less than 15 m/sec) and no applied magnetic fields, although current densities of 30 $MA/m^2$ were achieved.

The purpose of the present study was to extend the previous investigations in several ways. First, brushes were fabricated by essentially the same technique but were not contoured to the rotor diameter prior to etching. The effect of noncontouring might be expected to be most critical in small diameter devices as is the case of the present study. Second, previous experiments always utilized a single brush in a liquid metal flow field. In these experiments a more complete slipring coverage is obtained. Finally, higher velocities and magnetic field effects are studied in anticipation of using these brushes in a 300-kW superconducting generator.

## EXPERIMENTS

As with previous studies, the brushes used in this investigation are 50-μm-diameter niobium fibers in a copper matrix. Figure 1 is a photograph of the stock material at increasing magnification with the niobium appearing as little dots in the background of copper. The stock material is sliced at an angle of 15 degrees to provide the brush with additional flexibility. The circles are then cut and milled to the final brush shape. The milled pieces are degreased, and the sides and back are coated with beeswax to protect those areas from acid vapors. Several pieces are collected together and inverted over a nitric acid bath; etching proceeds by contact with the acid held in place by surface tension (see figure 2). Etching time is critical, approximately one-half hour for the size brushes used here. The brushes were etched to a final length of 0.5 cm within 10 percent as mea-

sured near the center of the brush. This technique may not be suitable for nonliquid metal-wetted fiber brushes, where uniformity may be essential, but was considered satisfactory for the present studies. Figure 3 shows scanning electron microscope (SEM) photographs of the brushes made.

The brushes are then assembled into a brush holder and crimped. An assembled slipring holder is shown in figure 4. The slipring is then placed in one channel of the 300-kW model test rig (11.4 cm diameter), and the other channel has a braid collector. Both brush and braid have approximately a 50-μm interference fit with the rotor surface. A copper fiber brush was used for a center tap. Photographs of both collectors are shown in figures 5 and 6. The overall experimental setup is shown in figure 7 where the 300-kW model rig has been placed in the bore of an electromagnet. The collectors are kept under an inert atmosphere of dry (less than 3 ppm), oxygen-free (less than 6 ppm) nitrogen cover gas. Five cubic centimeters of liquid metal $NaK_{78}$ were inserted into each collector.

During the experiments, rotor tip velocities varied up to 67 m/sec, currents up to 4,000 A, and magnetic field to 1.2 T. Typical experimental traces are shown in figure 8, while the variation of voltage drop with the field is shown in figure 9. The experiment was terminated abruptly by mechanical failure of the rotor and the rig was disassembled. Photographs of the brush and braid are shown in figure 10.

## RESULTS

Figure 8 is a direct comparison of the electrical characteristics of a liquid metal-wetted niobium fiber brush current collector with a liquid metal-wetted braid collector under similar conditions. The fiber brush collector has characteristics similar to the braid; this was found to be true for all conditions of the present study. As can be seen, the fiber brush collector does not show some of the occasional spikiness seen in the braid collector under these conditions.

Figure 9 is a typical plot of the voltage drop across the collectors as a function of applied magnetic field. Initially, it appears that the braid collector is deteriorating (higher voltage drops) with increasing field, while the brush collector is improving. This, however, is an artifact of the placement of the center tap which is located at a smaller diameter than either of the two sliprings. In the axial magnetic field, the intercepted flux induces a voltage which increases with field. When the effect is taken into account, the lower curve on figure 9 results. Now the brush appears to have the higher voltage drop with increasing field. This, however, is the result of the brush and braid sliprings being at slightly different radii and the fact that the brush and braid are conducting current in opposite directions. This results in a $J \times B$ body force in different directions in the two collectors, which affects the motional electromagnetic force. Figure 11 is a plot of theoretical calculations[5] of transport current against required voltage drop for a liquid metal collector with appropriate parameters for the present experiment. With no field, the transport current is speed independent, as expected. As magnetic field is increased, the voltage shifts to more negative values because of the $V \times B$ field developed. In addition, the slope of the line changes because of the $J \times B$ body forces modifying the velocity distribution. Therefore, as one attempts to transport positive current at successively increasing fields, the necessary voltage is less than for negative current, which explains the trend in figure 10. When this effect, as well as the infrared drop in the rotor, is taken into account the two collec-

tors have similar characteristics. The magnetic field, therefore, seems to have little if any harmful effect on the fiber brush collector.

The experiments were halted rather dramatically as the rotor came apart at 9,400 r/min. Surprisingly, there was little to no damage to the fiber brush collector while the braid did show some signs of distortion and damage. Figure 12 is an experimental tracing of the voltage drops when the damage occurred. Figure 12 shows the current is interrupted after the 1.2 T field is applied and just prior to failure. Figure 13 shows several SEM photographs of a typical part of the fiber brush after the experiment. There is some evidence of distortion of some of the fiber tips and may be the result of arcing during the rotor failure. Elemental x-ray analysis (figure 14) showed that the worn fiber (figure 13, location B) was niobium, while the little ball on the edge of the fiber (figure 13, location C) is mostly copper. This is compared to a fiber (figure 13, location A), which showed no sign of any wear or copper. This small amount of melting must be considered inconsequential compared with the overt lack of damage. However, portions of the braid showed significant distortion and melting.

## CONCLUSIONS

Niobium fiber brushes wetted with liquid metal $NaK_{78}$ were compared directly with NaK-wetted braid collector and found to operate as well or better under all conditions studied. The effects of noncontouring, higher tip velocities and magnetic fields were found to be minimal while the brushes were found to be resilient to a shock load. There is evidence of some damage to some of the fiber tips but this was far less than that appearing on the braid.

Further investigations with niobium fiber brushes are intended. Smaller diameter (25 $\mu$m) fibers will be studied as they may be more susceptible to the magnetic fields but, because of their smaller size, would be more desirable as a direct replacement for braid in the 300-kW machines.

Further data are required to obtain estimates of the viscous power losses with liquid metal-wetted fiber brush collectors.

Finally, the true test of any current collector is its operation in an electrical machine. The collectors described here will be operated in a 300-kW superconducting homopolar generator. This machine is a severe environment for any potential collector because it requires the collector to operate stably in a 5-T magnetic field while carrying continuous current densities of 26 $MA/m^2$.

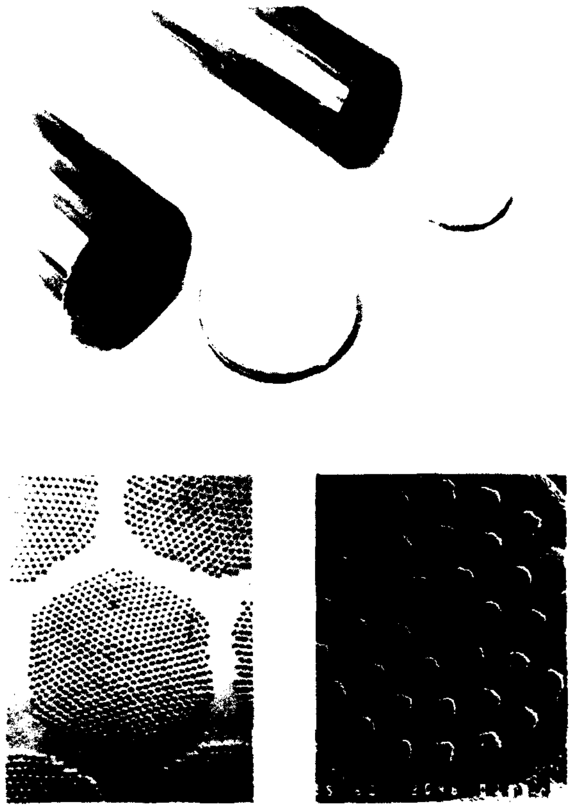

Figure 1. Niobium fibers in copper matrix.

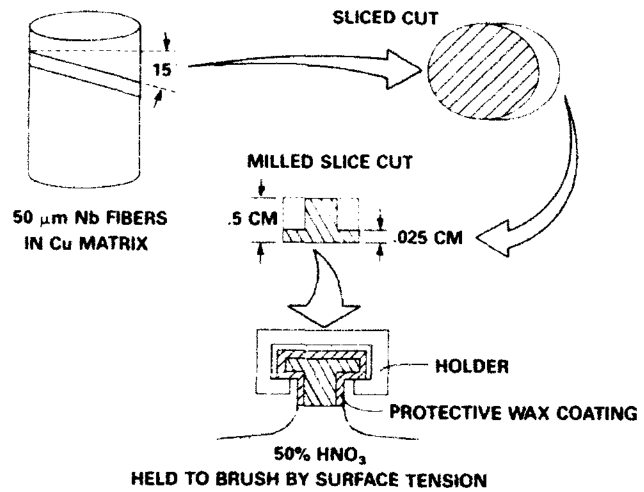


**Figure 2.** Fabrication method for niobium fiber brushes.

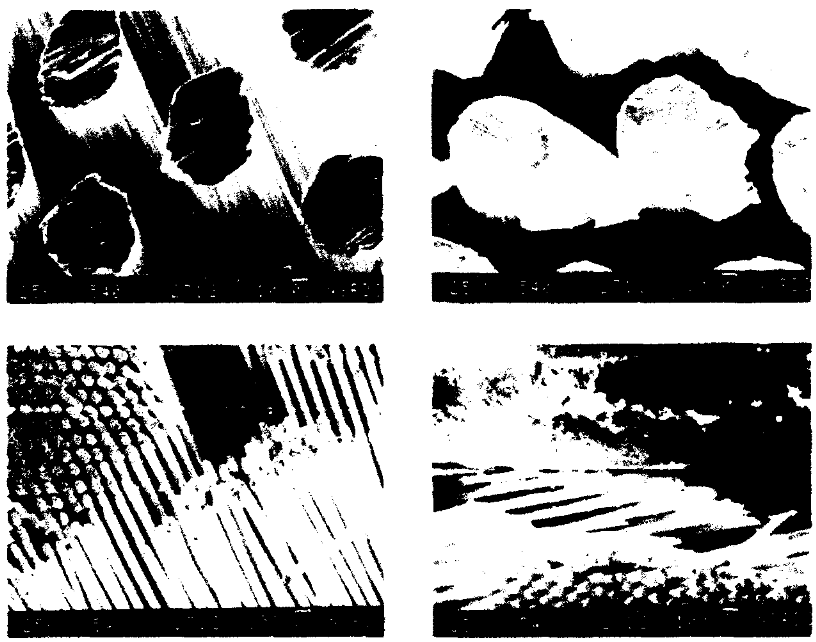

**Figure 3.** Scanning electron microscope photograph of niobium fiber brushes.

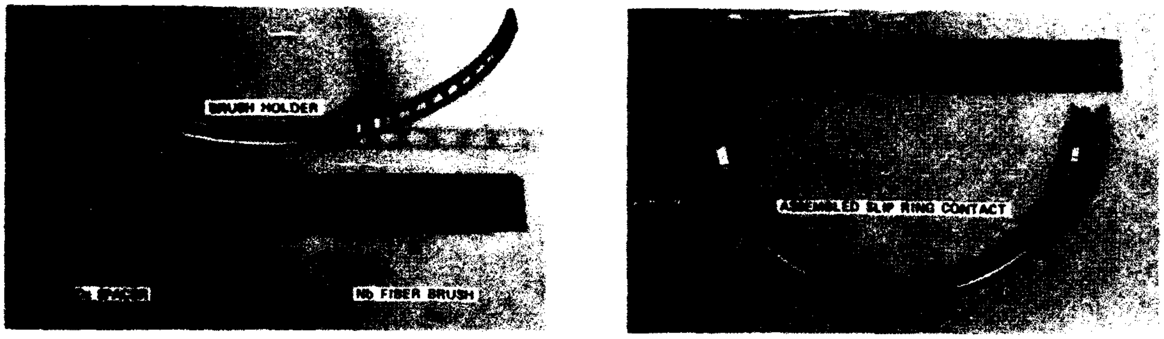


**Figure 4. Slip ring parts and assembled slip ring.**

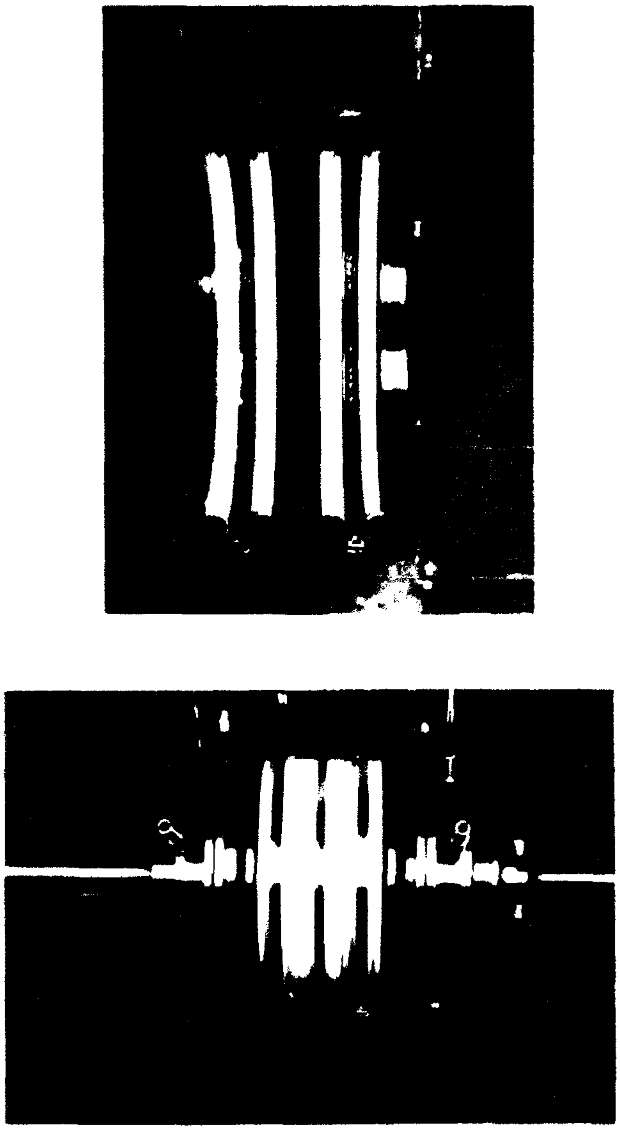

Figure 5. Niobium fiber brush slip ring and braid slip ring in 300-kW model test rig.

Figure 6. Detail of slip rings showing copper fiber brush center top.

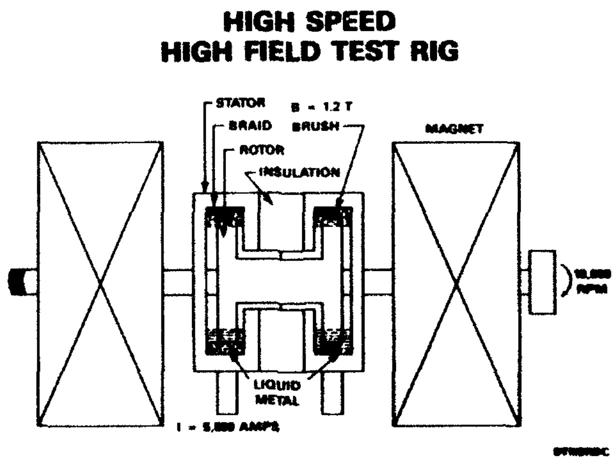


Figure 7. 300-kW model test rig setup.

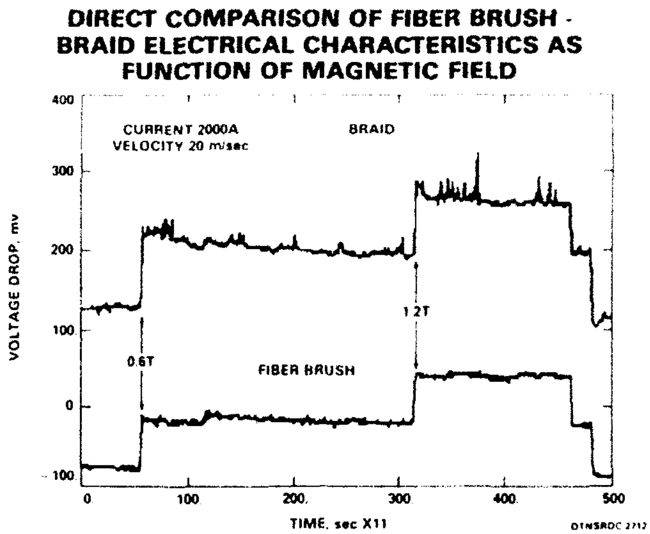


Figure 8. Direct comparison of fiber brush and braid electrical characteristics as a function of magnetic field.

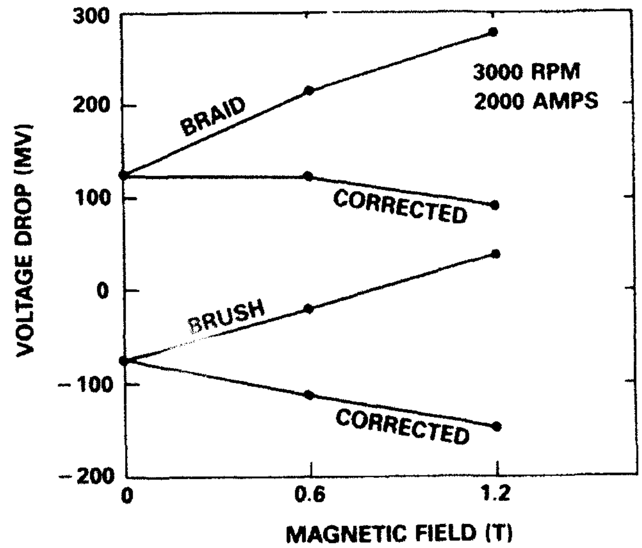


Figure 9. Collector voltage drop as a function of magnetic field.

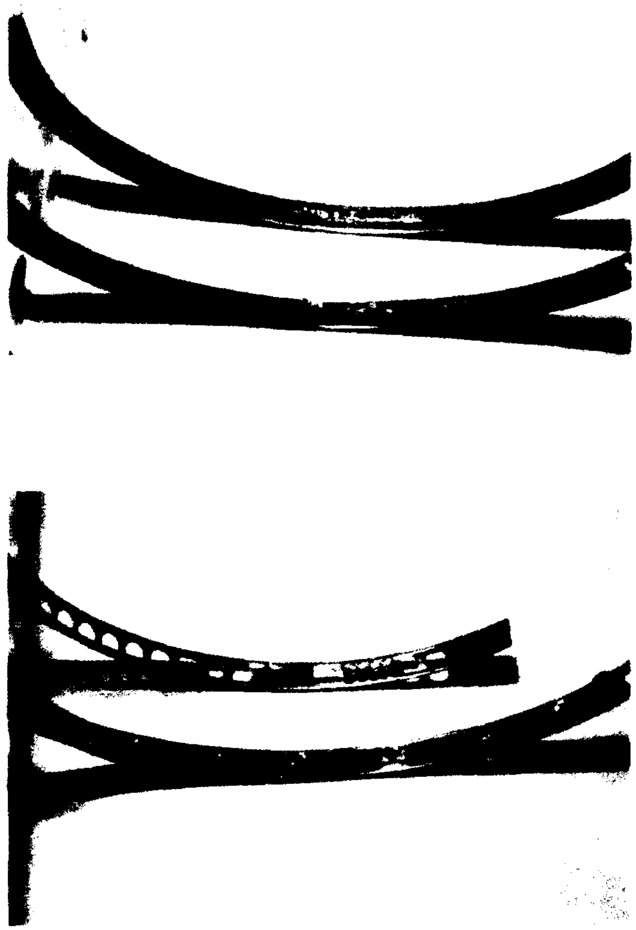

Figure 10. Niobium fiber brush and braid collector after experimental runs.

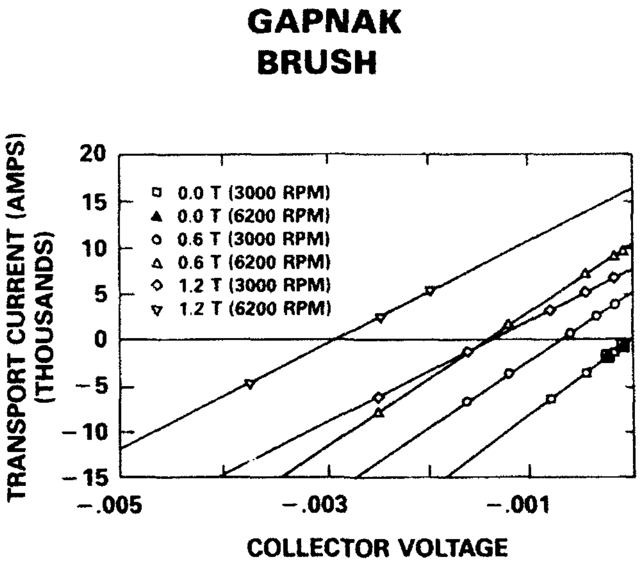


Figure 11. Theoretical calculation of transport current vs. original voltage drop.

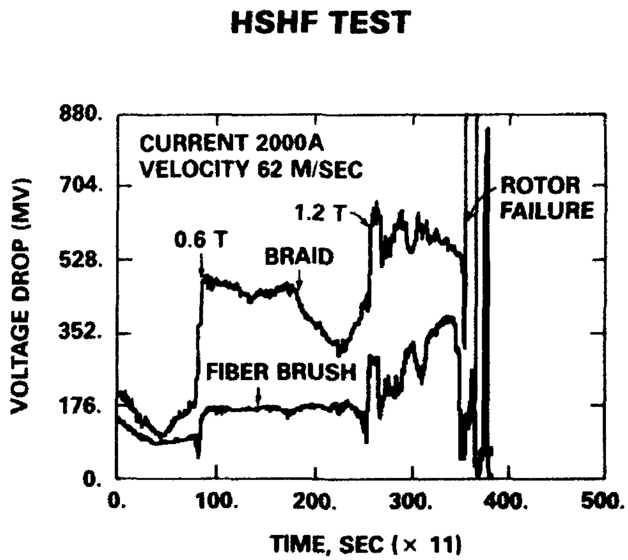


Figure 12. Comparison of niobium fiber brush and braid voltage drops.

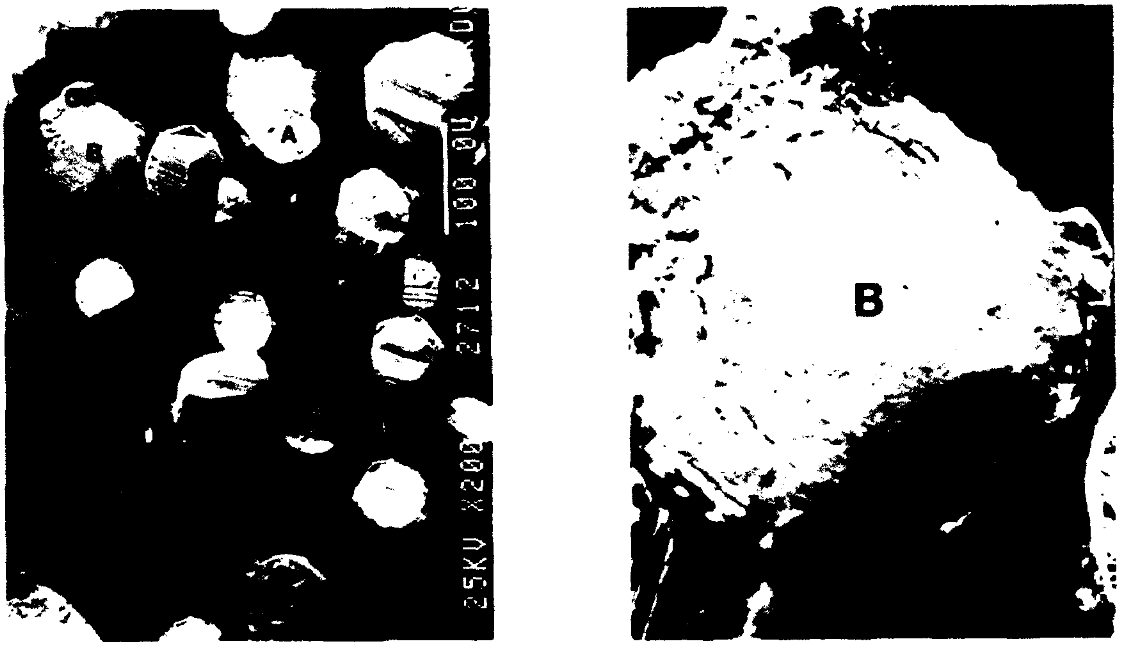


Figure 13. SEM of niobium fibers after test.

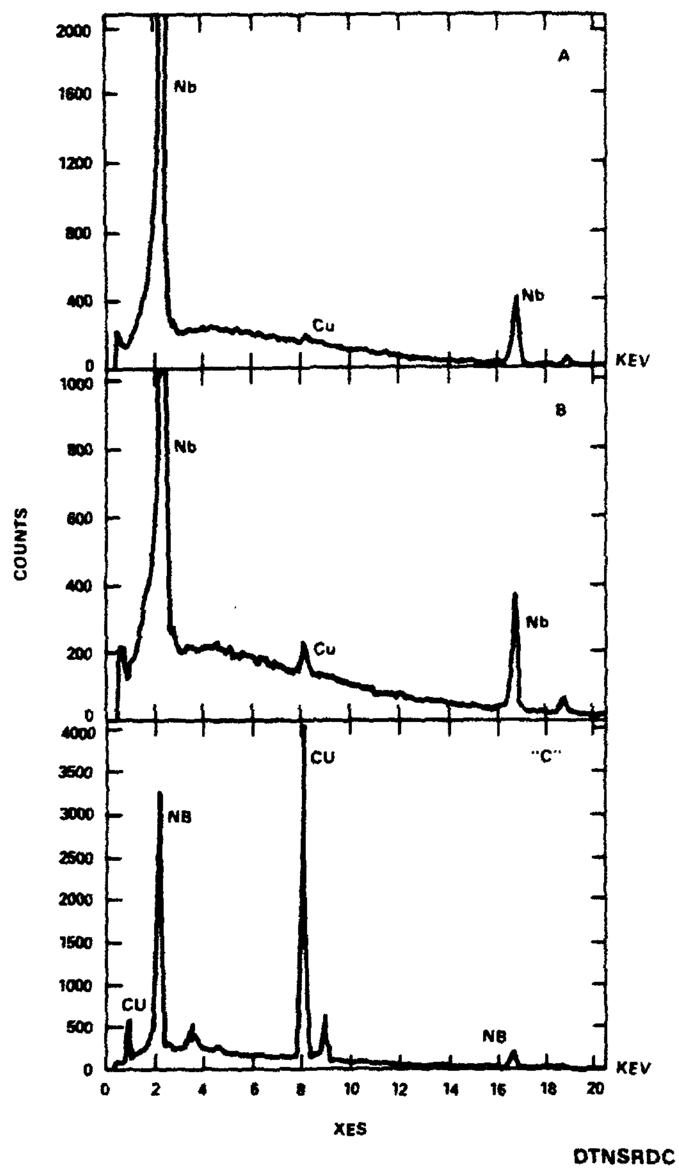


Figure 14. Elemental x-ray analysis of niobium fiber brushes after test.

## REFERENCES


1. Stevens, H.O., M.J. Superczynski, T.J. Doyle, J.H. Harrison, and H. Messigner, "Superconducting Machinery for Naval Propulsion," IEEE Transactions on Magnetics, vol., mag. 13, no. 1 (Jan 1977).

2. Doyle, T.J., and M.J. Cannell, "Development of Shaped Field Superconducting Motor," DTNSRDC Report No. 4178 (1974).

3. Cannell, M.J., and H.0. Stevens, "Acyclic Superconducting Generator Development, 400 Horsepower Generator Design," DTNSRDC Report No. PAS 81/14 (1982).

4. Sondergaard, N.A., "Studies of Liquid Metal Wetted Metallic Fiber Brush Current Collectors," Proceedings of the Second International Current Collector Conference, Annapolis, Md. (1983).

5. Triplett, M.D., and J.W. Griffith, "High Speed Narrow Gap Liquid Metal Current Collectors," Proceedings of the Second International Current Collector Conference, Annapolis, Md. (1983).

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